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Abstract – The aim of this paper was to develop an upscaling approach for the soil-crop model STICS in order to predict the impact of agricultural practices on nitrate leaching on both plot and regional scales. A case study was carried out on a 'Nitrate Vulnerable Zone' located in central France. The performance of the spatial approach was evaluated by accounting for all the spatial and temporal variability existing within the studied area. The results indicate that N leaching and nitrate concentration in drainage water were slightly underestimated; by 3 kg $N \cdot ha^{-1}$ (16%) and 8 mg $NO_3^- \cdot L^{-1}$ (11%), respectively. The STICS scaling approach was used to assess the effectiveness of "Good Agricultural Practice" established within the area over a seven-year period. The simulation results provided evidence that such a practice had reduced the nitrate concentration by about 30% (36 mg $NO_3^- \cdot L^{-1}$). However, the rate of nitrate leaching remains too large and further improvements to agricultural practices are required.

crop model ; STICS ; upscaling ; agricultural practices ; nitrate leaching ; decision support

1. INTRODUCTION

The need to limit nitrate leaching from agricultural sources, in order to protect human health, living resources and aquatic ecosystems and to prevent eutrophication, is well acknowledged.
This has been reinforced by the European Union Nitrate Directive (Council Directive 91/676/EEC), requiring each Member State to establish and implement a "Code of Good Agricultural Practice" and other additional measures, with the objective of reducing water pollution from nitrogen compounds in "Nitrate Vulnerable Zones" (NVZs). Good agricultural practices will differ between regions and much research is currently being undertaken to predict, and if necessary improve, the impact of good practices already established. This research is taking account of soil and climatic conditions, land use and agricultural practices in the different regions concerned.
As nitrate leaching on the regional scale cannot be measured directly, dynamic soil-crop models have been adopted to predict large-scale leaching [4, 22]. They are beginning to be used as technical aids for decision-making on the regional scale, particularly for assessing the effectiveness of the good agricultural practices supported by the European Union for reducing nitrate loss to water [3, 26]. Such models can predict crop yield, crop quality and water and nitrogen flows as a function of various soil, climate and agricultural practice interactions. However, most soil-crop models have been developed and tested for the scale of a homogeneous small plot. Their application on broader spatial scales introduces a number of difficulties. One difficulty is that the assumption of a homogeneous environment does not hold on scales larger than the plot. Input data to models, including cropping, management and environmental conditions, can vary both in space and in time. Another difficulty is the

performance of crop-soil models across a large range of variability of input data. Model evaluation on various scales is therefore essential to assess the quality of predictions. A third difficulty is the ability of soil-crop models to be used for decision support for N management on both the farm and regional scales. A classical approach for overcoming these complications is to use input data in an aggregated form [23, 27]. This approach contributes to uncertainty in the simulation results [24] and does not allow farmers, agricultural advisors, local agricultural representatives or public decision-makers to explore directly, and in detail, the implication of changes in agricultural practices on nitrate leaching. The first objective of the present study was to develop and assess an upscaling approach of a soil-crop model to predict the impact of agricultural practices on nitrate leaching on both plot and regional scales. We used the soil-crop model STICS, which is a deterministic, one-dimensional model for the simulation of water and nitrogen balances in soil and crops. A NVZ located in the “Petite Beauce” region, in central France, was chosen as a case study site. The originality of the work was to take into account the spatial and temporal variability of cropping systems and environmental conditions existing within the studied area. A second objective was to simulate agricultural scenarios according to the French “Code of Good Agricultural Practice” to assess and eventually improve the benefit of such practices within the studied NVZ. The general aim was to give a modelbased decision support tool for N management on various scales.

2. MATERIALS AND METHODS

2.1. STICS crop model

This section is limited to a brief description of the STICS model (version 4.1) used in this study. The reader can refer to several papers for more information about: (i) the theory and parameterisation (applied to wheat and corn) underlying this model [8]; (ii) an example of model validation for various wheat and maize crop situations in France [9]; (iii) sensitivity analysis of the model to its internal parameters [39]; and (iv) an overview of the model and presentation of the latest version 5.0 [7]. STICS simulates both agronomic variables (leaf area index, biomass, yield and input consumption) and environmental variables (soil profile water and contents, water drainage and nitrate leaching at the base of the soil profile). The data required to run the model relate to climate, cropping system (crop type and rotation, and agricultural practices) and soil properties (unchanging soil attributes and initial water and nitrogen profiles). STICS is a generic model easily adapted to various crop types and is able to simulate various pedoclimatic conditions without introducing strong bias [9].

2.2. Experimental site

2.2.1. Location and climate

The experimental site of Villamblain (740 ha) is located in the “Petite Beauce” region, in central France, 60 km south-west of Paris. This agricultural region has a modified oceanic climate with an annual average temperature of 10.5 °C. For the study period (1991–1999), mean annual rainfall (P) and potential evapotranspiration (PET) were 587 and 788 mm, respectively. Annual rainfall varied from 390 mm to 748 mm over the study period. The potential evapotranspiration was less variable, ranging from 737 to 827 mm. The mean value of the annual water deficit (PET-P) was 201 mm.

2.2.2. Soils

The soils of the region are developed in silty clay loam materials overlying Miocene lacustrine limestone that was cryoturbated in its upper part during the Quaternary [29, 30]. A published soil survey [19, 40] describes the main soil types and their spatial distribution over the experimental site. According to the FAO soil classification scheme [21], the soil types identified include:

- Haplic Luvisols, which lie over cryoturbated materials.
  These soils are developed in loam, the thickness of which exceeds 0.80 m. They account for 6% of the experimental area.

- Eutric Cambisols, which are shallow profiles developed in loam (less than 0.80 m). They lie over soft limestone, cryoturbated materials or hard limestone, and represent 26% of the experimental area.
- Haplic Calcisols, which are underlain by a variety of materials, soft limestone, shallow layers of cryoturbated materials, thick layers of cryoturbated material and hard limestone. The thickness of these soil profiles usually varies between 0.45 and 0.75 m. They are present on 20% of the experimental area.

Calcareous soils, which cover 48% of the experimental area. They are represented by Calcaric Cambisols and Rendzic Leptosols. They lie over soft limestone, cryoturbated materials and hard limestone. Their thickness ranges from 0.30 to 0.75 m. About 50% of the experimental area is composed of shallow soils, the thickness of which is less than 0.60 m. The available water content (AWC) of the soils across the entire experimental site varies between 50 and 180 mm. The pedological variability evident at this site is similar to that of the entire “Petite Beauce” region [6, 12, 13]. A soil database for the experimental site, including a soil description for the mapping units, was established. The soil description provided for each horizon consists of the following : depth, texture, active lime content, and nature and content of stone materials. Other descriptors for the full soil profile include : type of substratum, type of parent rock, soil type, and depth of any physical or chemical obstacle to plant roots.

2.2.3. Land use and agricultural practices

About 91% (670 ha) of the experimental area is cropped. The remaining area (70 ha) corresponds primarily to woods. About 85% of the cultivated area is irrigated. Land use and agricultural practices on the experimental site are known. Spring crops were grown on 42% of the total experimental area between 1991 and 1998. They include mainly maize (27%), green peas or beans (8%) and barley (4%). Winter crops were grown on 42% of the area and included soft wheat (27%), hard wheat (11%) and rapeseed (3%). Fallow land represented 6% of the area. It was composed of sown cover crops (white mustard, rye and ryegrass), industrial fallow crops (flax, sunflower and rapeseed) and bare fallow. The experimental site drains into a large aquifer, the concentration of which exceeds 75 $mg \cdot L^{-1}$ nitrate, and contributes to N pollution. Agricultural practices of the site have been modified since 1991, in accordance with the regional Action Programme established within NVZs. This Action Programme includes the measures prescribed in the French “Code of Good balance. The modifications added to the conventional practices consist of :

- Managing nitrogen fertilisation, both the rate and time of application. The N application rate is now based on a predictive balance-sheet method [38]. The recommended N fertiliser is estimated once a year in each plot of the site, using the AZOBIL model [31]. Measurements of soil mineral nitrogen (SMN) have been conducted at harvest, and at the beginning and end of winter ; the effects of N rate on crop yield (maize, winter wheat and barley) have been established too.
- Controlling SMN and nitrate leaching in autumn and winter, by introducing cover crops. The cover crops used are white mustard and phacelia. They are sown in August after wheat, barley or peas, and are destroyed in November. After November, the low temperatures markedly reduce both cover crop growth and N mineralisation in soil.

The farmers thus reduced the total amount of N supplied to crops by 27 kg $N \cdot ha^{-1} \cdot year^{-1}$ on average (from 212 to 185 kg $N \cdot ha^{-1} \cdot year^{-1}$) between 1991 and 1998, without any decrease in yield. This decrease in N supply was particularly evident for maize crops, with an average reduction of 55 kg $N \cdot ha^{-1} \cdot year^{-1}$ (from 219 to 164 kg $N \cdot ha^{-1} \cdot year^{-1}$), that represents a 25% reduction compared with conventional fertiliser rates [43]. The area of cover crop increased from 0 to 40% between 1990 and 1998. Less than 8% of the area remained uncovered in autumn and winter, whereas the uncovered area was about 50% before 1990.

2.2.4. Measurements

A set of 8 lysimeters was constructed: two lysimeters in each of the four locations of the experimental site (Fig. 1), which were close and received the same crop and soil conditions (replicates). The lysimeters were undisturbed monoliths of 1 m^2 area and 1.5 m depth. Water drainage and nitrate leaching at the base of the lysimeters were monitored weekly from 1994 to 1999.

Soil water content (SWC) and SMN in the soil profile were measured three times per year (at harvest, and at the beginning and end of winter) in each plot of the experimental site during the period 1991–1999. SWC and SMN were also measured in the vicinity of each lysimeter. Thus, between 24 and 53 SWC and SMN sampling locations were considered each year, according to the pattern of plots. An example of the SWC and SMN sampling design is given for the year 1997–1998 in Figure 1. For each year, SWC and SMN measured at the time of harvest of the previous crop were used for model initialisation. The SWC and SMN measured at the beginning and end of winter and at the time of harvest of the simulated crop were used for model validation.

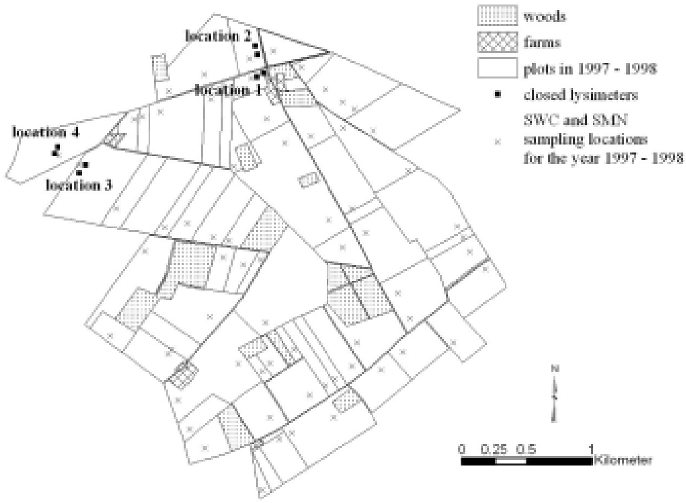

Figure 1. Global sampling design of the experimental site.

2.3. Approach developed

2.3.1. Simulation and validation on the lysimeter scale

The STICS model was first evaluated on the lysimeter scale. Several simulations were performed using different cropping systems, pedological properties and climatic conditions. Two simulation types were carried out for the period between December 1994 and August 1999 :

- The first type is an “annual simulation”; the STICS model was initialised at the beginning of each crop cycle using measurements of SWC and SMN taken at the time of the preceding harvest in the vicinity of the lysimeters.
- The second type is a “continuous simulation”; the STICS model was initialised only at the beginning of the first year (1994). It simulated SWC and SMN during the following years.

STICS was evaluated over 1994–1999 for five variables of interest : cumulative drainage over one crop cycle, cumulative N leaching, mean nitrate concentration in drainage water and SWC and SMN at harvest. Several statistical criteria were used to evaluate the model performances [1]. These included the mean error (ME) and its relative value in % (ME%) :

$$ME = \frac{1}{n}\sum_{i=1}^{n}(O_i - P_i) \text{ and } ME\% = \left(\frac{ME}{\bar{O}}\right) \times 100$$

and the root mean square error (RMSE) and its relative value in % (RMSE%) :

$$RMSE = \sqrt{\frac{1}{n}\sum_{n=1}^{n}(O_i - P_i)^2} \text{ and } RMSE\% = \left(\frac{RMSE}{\bar{O}}\right) \times 100$$

where n is the number of observations, O the observed value, $\bar{O}$ the mean of the observed values and P the value predicted by the model. For an unbiased simulation, the ME should be close to zero, while for an accurate simulation the RMSE should be small.

2.3.2. Simulations over the experimental site

2.3.2.1. Representation of the spatial and temporal variability of input data

To use the STICS model on the scale of the experimental site, an assumption must be made that environmental variables are system (including land use, crop rotation and management) and soil properties (including permanent soil features and initial conditions) vary spatially. In our case, the different weather stations located around the experimental site indicated that the climatic conditions (in particular daily rainfall) were similar across the site. The spatial variability of crops and soils was related to each spatial unit [23]. Since the pattern of plots varied from year to year, the smallest common pattern of plots was defined over the study period by overlaying the different land-use maps (Fig. 2a). The spatial units obtained were therefore homogeneous on a cropping level (type and sequence of the crops). Two land-use maps were defined for each year; one for the main crops and one for the cover crops. Overlaying the fourteen land-use maps for the period 1991–1998 resulted in the definition of 320 spatial units. Each unit was characterised by its crop management parameters obtained by systematic surveys ; soil preparation and tillage with ploughing-in of residues (date, depth, type of residues, quantity of residues and C/N value), sowing (date, depth, density and variety), mineral and organic fertilisation, irrigation and harvesting. We incorporated into the simulations all the spatial and temporal variability of the agricultural practices of the region. Each spatial unit, having a specific cropping sequence, may include several soil types with different properties (thickness, AWC, etc.). To obtain spatial units homogeneous on both cropping and pedological levels, an overlaying of the smallest common pattern of plots and of the soil map was performed (Fig. 2b). This overlaying led to the definition of 832 spatial units homogeneous for crops and soils, which constitute the basic simulation units (SUs). The permanent soil parameters required by the model were estimated from the soil database, by applying expert rules or pedotransfer rules to each soil map unit. Thus, water content at field capacity, water content at permanent wilting point and bulk density were determined for each soil horizon according to depth, textural class, stone content, lime content and soil type [2, 15, 40]. Initial values of SWC and SMN in the soil profile were needed for each simulation unit (Fig. 2c). However, the measurements of SWC and SMN were not performed in each SU.

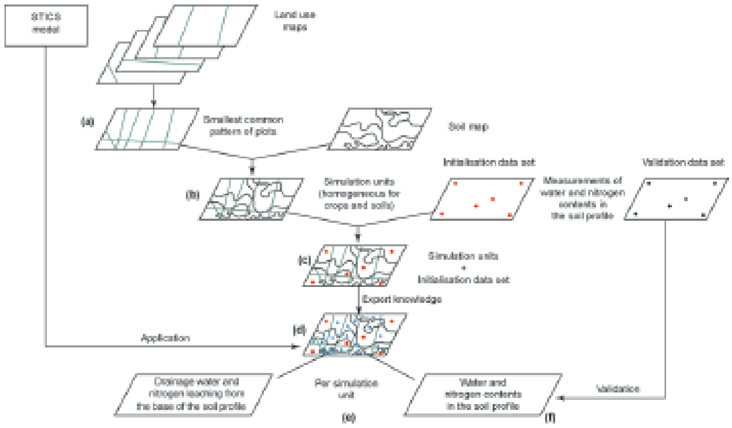

Figure 2. A schematic diagram for upscaling the STICS model.

For example, for the year 1992–1993, SWC and SMN measurements allowed the initialisation of only 53 of the 832 SUs, i.e. approximately 16% of the total area. A procedure based on the previous crop type, crop management and soil type was developed to estimate SWC and SMN in each SU (Fig. 2d). This "expert" procedure consists of searching among the SUs where SWC and SMN were measured, for those with the most similar cropping and pedological characteristics. The measured SWC and SMN values (or their means) are assigned to the SU that lacks measurements under the following assumptions for each soil layer :

- the SMN profile is identical to that of the measured SU, and
- the SWC profile, expressed as a percentage of the AWC, is the same as that of the measured SU.

Figure 3 presents the results of the application of such a procedure to the whole experimental site for the year 1992–1993. The estimated and measured SWC and SMN values are relatively clustered, which demonstrates the absence of bias in the "expert" procedure. The discrepancies are mainly related to the over-representation of stony and calcareous soils in the SUs that lack measurements.

2.3.2.2. Simulation types

The STICS model was then applied to each SU to simulate the temporal changes in SWC and SMN, as well as water drainage and N leaching at the base of the soil profile (Fig. 2e). As mentioned before, two simulation types were carried out over the experimental site, for the period between the summer of 1991 and the summer of 1998; these were the "annual simulation" and the "continuous simulation". All spatial analyses were performed using GIS Arc/Info version 7.2.1 [20], which was interfaced with STICS [25]. The STICS model was configured with interactive tools of the GIS, in particular the macro-language (AML). This macro-language allows the querying of geographic databases, the constituting of STICS input files and the running of simulations. It also makes possible the importing of STICS output variables, automatic spatial averaging and the visualising of spatial patterns of results [36].

2.3.2.3. Validation procedure

Annual simulations were performed with the alternative agricultural practices set up after 1991. They predict the nitrate leaching rate as well as the main factors controlling the spatial and temporal variability of this leaching. They were used to check the performance of the STICS model on the site scale. The model was evaluated over the 1991–1998 period, on SWC and SMN measured in the soil profile at the end of winter (January or February) (Fig. 2f). The statistical criteria used are the same as defined before.

2.3.2.4. Evaluating the impact of agricultural practices

The continuous simulation was used to compare, over the period 1991–1998, alternative agricultural practices set up after 1991 versus conventional agricultural practices set up before 1991. The initialisation of the STICS model was done in 1991, since measurements of conventional practices were not available after 1991.

3. RESULTS

3.1. Local simulation of nitrate leaching

3.1.1. Annual simulations

The results of the measurements and annual simulations are detailed for two replicate lysimeters located at location 2 (Fig. 1). Mean annual drainage measured at the base of these lysimeters (Tab. Ia) varied from 67 to 212 mm over the study period (1995–1999). For all of the lysimeters at the experimental site, the largest drainage values were observed under maize and winter wheat and the smallest values under green peas and winter rapeseed. With regard to annual N leaching, mean measured values ranged from 6 to 22 kg $NO_3^-\cdot L^{-1}$, with the largest values under maize, winter rapeseed and winter wheat and the smallest value for green peas which were not fertilised. Nitrate concentration in drainage water varied from 40 to 67 mg $NO_3^-\cdot L^{-1}$. The mean value was 48 mg $NO_3^-\cdot L^{-1}$ over the study period, just less than the EU limit for drinkable water (50 mg $NO_3^-\cdot L^{-1}$). The largest nitrate concentrations were observed under winter wheat, maize and winter rapeseed and the smallest concentrations under green peas.

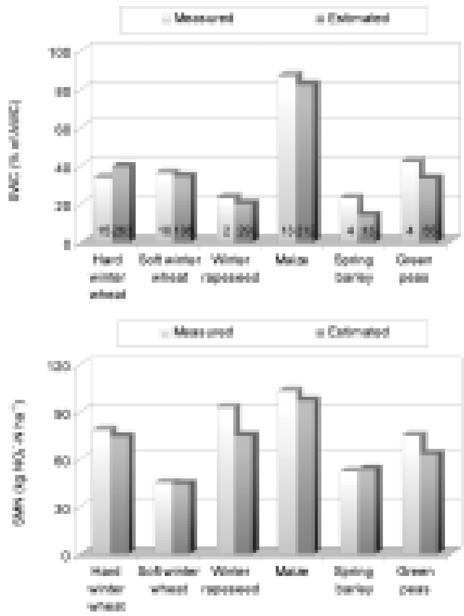

Figure 3. Mean values of SWC and SMN according to the previous crop, for the year 1992–1993. The crops represented here covered 88% of the area of the experimental site in 1992–1993. The numerals on the histograms represent the number of measured or estimated values.

(a)	Cumulative drainage (mm)			Cumulative N leaching ($kg \cdot N \cdot ha^{-1}$)			Nitrate concentration ($mg \cdot NO_3^- \cdot L^{-1}$)		
	Measured	Simulated		Measured	Simulated		Measured	Simulated	
Crop	Lysimeters	A*	C*	Lysimeters	A*	C*	Lysimeters	A*	C*
Maize 95	212	202	202	22	23	23	46	50	50
Winter wheat 95/96	138	145	134	13	10	5	40	31	16
White mustard 96	0	0	0	0	0	0	–	–	–
Green Peas 97	67	49	54	6	3	6	40	29	48
White mustard 97	0	0	0	0	0	0	–	–	–
Winter wheat 97/98	120	120	131	13	8	16	49	29	53
Winter rapeseed 98/99	116	89	84	17	13	3	67	66	15
Total 95/99	652	605	605	71	57	52	48	42	38

(b)	SWC at harvest (mm)			SMN at harvest ($kg \cdot N \cdot ha^{-1}$)		
	Measured	Simulated		Measured	Simulated	
Crop	Plot	A*	C*	Plot	A*	C*
Maize 95	416	389	389	42	60	60
Winter wheat 95/96	261	288	287	39	25	39
White mustard 96	no data	346	367	42	31	36
Green Peas 97	393	420	420	125	81	77
White mustard 97	352	346	367	39	66	51
Winter wheat 97/98	294	292	292	61	33	33
Winter rapeseed 98/99	no data	328	329	no data	51	39
Mean 95/99	343	347	351	58	49	49

Table I. Comparison of measured and STICS simulated values (A* = annual simulations; C* = continuous simulations) on the lysimeter scale under different crops: (a) cumulative drainage, cumulative N leaching and mean nitrate concentration in drainage water at the base of the two lysimeters (two replicates) at location 2. The measured values are the average of the two replicates. (b) SWC and SMN (0–1.5 m) at harvest in the vicinity of the two lysimeters at location 2.

SWC measured in the vicinity of the lysimeters at harvest (Tab. Ib) varied from 261 to 416 mm over the study period. These values represent from 0 to 85% of the AWC. The greatest SWC was observed at maize harvest. This is related to the late time of harvest (in October) and the ample water supply under irrigation. The smallest SWC was measured at the winter wheat harvest (in July). SMN at harvest ranged from 39 to 125 kg $N \cdot ha^{-1}$, with the greatest residual N observed under green peas and the least under white mustard (cover crop). Generally, a good agreement was found between measured and simulated annual values of cumulative drainage and N leaching in most situations (Tab. Ia, col A*). Nevertheless, some biases of simulation were observed. These biases are mainly specific to the type of simulated crop. At maize harvest in 1995 (Tab. Ib, col A*), SWC was underestimated by 27 mm and SMN was overestimated by 18 kg $N \cdot ha^{-1}$. This could result from an inadequate prediction of maize root density by the model, particularly for soils lying on cryoturbated materials. Soils lying on cryoturbated materials are difficult to parameterise. They are likely to impose constraints on root distribution. They also allow the capillary rise of water and nitrate, which is neglected by the model. To partly overcome this limitation of the model, we assumed that the depth of water and nitrogen extraction by the plant is a little deeper than the actual depth of rooting. Using this estimated depth, STICS overestimated water and nitrogen uptake in the deeper layers, just above the estimated depth of extraction for water and nitrogen, whereas the water content in the upper layers was overestimated, particularly during the irrigation periods [40, 45]. The high water content simulated by the model in the upper layers led to an overestimation of the soil N mineralisation [40]. These biases, specific to maize in particular soils, occurred at the end of the crop cycle after the drainage period. Therefore, they are of little consequence to cumulative drainage and N leaching for this type of simulation. For the green pea crop in 1997, SMN at harvest was underestimated by 44 kg N·ha^{-1}. In STICS version 4.1, green peas were not simulated. Therefore, we adapted the spring wheat module in order to simulate soil attributes under green peas. The STICS development stages for spring wheat were reduced. These short stages and the absence of N fertilisation led to the simulation of a crop under high nitrogen stress. The N consumption by the crop was less than the N mineralisation rate. Thus, the model predicted a large SMN at harvest (81 kg N·ha^{-1}) even though the crop was not fertilised. This situation is close to that of a green pea crop. However, the SMN estimated at harvest remained less than the measured SMN, as symbiotic fixation by the green pea was not taken into account. In contrast, cumulative drainage and N leaching were correctly simulated (Tab. Ia, col A*).

3.1.2. Continuous simulations

The results of the continuous simulations (Tab. Ia, b, col C*) show that the discrepancies between measured and simulated values are more significant for this type of simulation than for the annual simulations. In particular, the simulations of N leaching and nitrate concentration are slightly worse for the continuous simulations than for the annual simulations. This is due to the propagation of errors during the continuous simulations. For example, the underestimation by the model of SWC at the maize harvest in 1995 led, for the following winter wheat crop, to the simulation of smaller values of water drainage and N leaching than those measured (Tab. Ia, col C*). However, for the various variables of interest (cumulative drainage and N leaching, nitrate concentration of drainage water, and SWC and SMN at harvest), simulated values with the continuous simulations were within the confidence interval of measured values.

3.1.3. Validation procedure

Validation results for the annual simulations are given for the eight lysimeters at the four locations in Table II and Figure 4. As expected, the variability of conditions existing across the four locations is more significant than that within one location. This makes it possible to test the model performance across a wider range of pedoclimatic conditions. The cumulative drainage was well reproduced by the model, with a ME of 9 mm (8%) and a prediction error (RMSE) of 36 mm (29%) for all crops. The correlation coefficient was 0.92. We obtained, at best, a prediction error of 13% for drainage under wheat. For maize and winter rapeseed, drainage was less successfully simulated. The large RMSE (60 mm) for drainage under maize was mainly due to one situation with very ample water supply. In this particular case, STICS did not reproduce the spring and summer drainage, which resulted in a large underestimation of cumulative drainage (Fig. 4a). The reason behind this error could be the inadequate prediction of root density under maize, which led to an overestimate of water and nitrogen uptake in the deeper layers at the end of the crop cycle and therefore an absence of drainage for this period. For winter rapeseed, the ME value was correct (–19%) whereas the RMSE value was too large (56%). The limited number of measurements did not allow us to explain the discrepancies between measured and simulated values of drainage under winter rapeseed. SWC at harvest was simulated very well, whatever the crop. The mean error was 1 mm (nearly 0%) and the prediction error was 31 mm (9%) for all crops. This is by far the most reliable part of the STICS model [9]. The SWC at maize harvest was slightly underestimated in all the situations (Fig. 4b), for the same reason as that described before. With regard to cumulative N leaching and SMN at harvest, the results were less satisfactory. Cumulative N leaching was underestimated by 3 kg N·ha^{-1} (16%) on average. The ME values varied between 0 and 7 kg N·ha^{-1} according to the type of crop. The prediction errors for N leaching ranged from 3 to 14 kg N·ha^{-1}, with a mean value of 10 kg N·ha^{-1} (49%). The relative RMSE values were quite similar for all the crops (between 44 and 46%). As for N leaching, the simulations concerning SMN at harvest were biased. The ME value was 21 kg N·ha^{-1} (27%) on average and the prediction error was 39 kg N·ha–1 (48%). The values of these statistical criteria are similar to those found by Brisson et al. [9] for SMN simulations for a wide range of wheat and maize crop situations in France. The underestimation of SMN at harvest was related to the overestimation of N consumption by the plant at the end of the growing cycle, in particular for maize. For one maize crop situation with an ample nitrogen supply, the STICS model did not manage to reproduce the large amount of SMN at harvest (Fig. 4b).

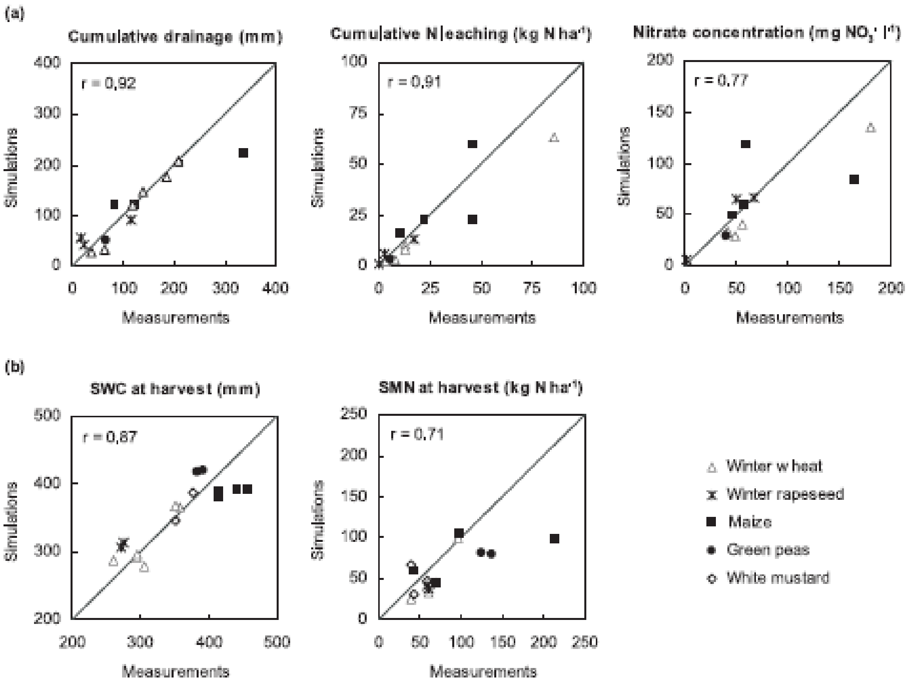

Figure 4. Comparison of measured and simulated values for annual simulations on the lysimeter scale: (a) cumulative drainage, cumulative N leaching and mean nitrate concentration in drainage water at the base of the eight lysimeters at four locations; (b) SWC and SMN (0–1.5 m) at harvest in the vicinity of the eight lysimeters at four locations. Points are the crop cycles indicated in Table II. Lines are 1:1 lines.

The results for nitrate concentration in drainage water are slightly better than those for N leaching and SMN at harvest. The nitrate concentration was underestimated by 8 mg $NO_3^-{\cdot}L^{-1}$ (11%) on average. The RMSE value was 32 mg $NO_3^-{\cdot}L^{-1}$ (42%) for all crops. A smaller prediction error was obtained for nitrate concentration in water draining under wheat, with a value of 9 mg $NO_3^-{\cdot}L^{-1}$ (15%). The large prediction error for maize was mainly due to two situations (Fig. 4a), one of which corresponded to the situation where STICS did not simulate well the spring and summer drainage, causing a larger nitrate concentration to be predicted for the drainage water.

The comparison of the values measured on the lysimeters with the values estimated by STICS for annual or continuous simulations, showed that this model could simulate correctly the nitrate leaching for various agronomic and environmental conditions existing within the experimental site. This result allowed the upscaling of the model over the whole experimental site.

(a)

Crop cycle	Cumulative drainage (mm) n	$\overline{O}$	ME	ME%	RMSE	RMSE%	Cumulative N leaching (kg N ha^{-1}) n	$\overline{O}$	ME	ME%	RMSE	RMSE%	Nitrate concentration (mg $NO_3^- l^{-1}$) n	$\overline{O}$	ME	ME%	RMSE	RMSE%
Winter wheat	6	126	9	7	16	13	5	25	7	30	11	44	5	86	20	23	24	28
Winter rapeseed	3	51	–10	–19	29	56	3	7	0	2	3	46	3	57	–6	–10	9	15
Maize	4	189	23	12	60	32	4	31	1	3	14	44	4	73	4	6	50	68
Green peas	1	67	18	27	18	27	1	6	3	46	3	46	1	40	11	27	11	27
White ustard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
All crop cycles	*14*	*124*	*9*	*8*	*36*	*29*	*13*	*21*	*3*	*16*	*10*	*49*	*13*	*75*	*8*	*11*	*32*	*42*

(b)

Crop cycle	SWC at harvest (mm) n	$\overline{O}$	ME	ME%	RMSE	RMSE%	SMN at harvest (kg N ha^{-1}) n	$\overline{O}$	ME	ME%	RMSE	RMSE%
Winter wheat	6	310	–4	–1	18	6	5	66	16	25	20	30
Winter rapeseed	2	273	–37	–13	37	13	2	59	19	33	20	33
Maize	4	433	44	10	47	11	4	106	30	28	61	57
Green peas	2	389	–30	–8	30	8	2	131	51	39	52	40
White mustard	2	364	–2	–1	9	2	3	47	–1	–3	18	39
All crop cycles	*16*	*353*	*1*	*0*	*31*	*9*	*16*	*80*	*21*	*27*	*39*	*48*

Table II. Validation results for annual simulations on the lysimeter scale under different crops: (a) cumulative drainage, cumulative N leaching and mean nitrate concentration in drainage water at the base of the eight lysimeters at four locations. n is the number of crop cycles observed at the four locations over the study period (1995–1999). Each crop cycle corresponds to one location and a mean measured value calculated from the two lysimeters' measurements at this location. (b) SWC and SMN (0–1.5 m) at harvest in the vicinity of the eight lysimeters at four locations.

3.2. Spatial simulation of nitrate leaching

3.2.1. Example of spatial results

The mean values of cumulative drainage, cumulative N leaching and nitrate concentration for the study period (1991–1998) are given for each SU of the experimental site in Figure 5. These three variables showed a high variability across the experimental site; mean annual drainage ranged from 70 to 261 mm, mean annual N leaching from 5 to 100 kg $N \cdot ha^{-1}$ and mean nitrate concentration from 5 to 285 mg $NO_3^- \cdot L^{-1}$. The effect of soil type (curved black lines) and land use (straight black lines) on the variability of the results, including the effect of the crop and the associated agricultural practices, is visible on the simulation maps (Fig. 5).

3.2.2. Validation procedure

Table III summarises the validation results of the spatial model for annual simulations. The mean error between measured and simulated values of SMN in January or February varied between –1 and +21 kg $N \cdot ha^{-1}$, depending on the year. During the entire period of study (1991–1998), the SMN at the end of winter was underestimated by 9 kg $N \cdot ha^{-1}$ (24%) on average. The ME variability could be related to the combined effects of cropping system, pedological properties and climatic conditions, which differed from one year to another. Even for a given crop, the bias of simulation varied according to the year, owing to various crop rotations, farming techniques and pedoclimatic conditions. For example, under winter wheat, the ME was –2 kg $N \cdot ha^{-1}$ (–6%) for the year 1997–1998, whereas it was +15 kg $N \cdot ha^{-1}$ (21%) for the year 1991–1992. The underestimation of SMN in January or February could be attributed to an overestimation of nitrogen uptake by cover crops. The RMSE was rather constant between years. For the entire period of study, the model's prediction error was 23 kg $N \cdot ha^{-1}$ (61%) on average. The standard deviations of the simulated values were slightly larger than those of the observed values; 26 and 22 kg $N \cdot ha^{-1}$ on average, respectively. Thus, the STICS model correctly reproduced the spatial and temporal variability existing within the experimental site.

Figure 5. Simulation maps of mean annual values over the period 1991–1998 of: (a) cumulative water drainage, (b) cumulative N leaching, and (c) nitrate concentration in drainage water. Black lines are the borders of the SU.

	SMN in winter (January or February) (kg N ha^{-1})								
Year	n	$\overline{O}$	STD_O	$\overline{P}$	STD_P	ME	ME%	RMSE	RMSE%
91/92	24	65	29	44	26	21	32	35	54
92/93	43	40	19	32	31	8	20	22	55
93/94	46	32	15	24	20	8	24	21	65
94/95	47	29	17	30	31	–1	–3	22	76
95/96	49	32	20	27	28	5	14	20	63
96/97	48	39	22	26	21	14	35	19	49
97/98	52	36	19	23	22	13	37	23	65
91/98	309	37	22	28	26	9	24	23	61

Table III. Validation results for annual simulations on the experimental site scale (STD0: standard deviation of the observed values; : mean of the predicted values; STDP: standard deviation of the predicted values).

Year	PET-P (01/10–31/03) *(01/10–30/04) (mm)	Mean drainage (mm yr^{-1})	Mean N leaching (kg N ha^{-1}·yr^{-1})	Nitrate concentration (mg NO_3^-·L^{-1})	A* (%)
91/92	47	48	18	166	29
92/93	155	182	49	118	21
93/94	193	171	42	109	31
94/95	224	241	38	69	43
95/96	117	131	24	80	38
96/97	161	158	31	86	33
97/98	86 (161*)	155	25	72	50
Mean 91/94	132	134	36	120	27
Mean 94/98	166	172	29	76	41
Mean 91/98	151	155	32	92	35

Table IV. Results of annual simulations for the experimental site: mean drainage, mean N leaching and nitrate concentration in drainage water at the base of the soil profile under alternative agricultural practices (A*: relative area with a mean concentration < 50 mg NO_3^-·L^{-1}).

3.2.3. Impact of alternative agricultural practices on nitrate leaching

3.2.3.1. Simulated water drainage and nitrate leaching

The results of the annual simulations, performed with the alternative agricultural practices, are summarised in Table IV. The cumulative drainage (and therefore leaching) over the whole experimental site was computed as the mean of the cumulative drainage (and therefore leaching) of each SU weighted by its area. The mean nitrate concentration is the ratio between the mean cumulative N leaching and the cumulative water drainage. Cumulative drainage and N leaching showed a strong temporal variability. Cumulative drainage was related to the water balance (PET-P) in autumn and winter. Nitrate concentrations also varied considerably over time. They were very large during the first three years (between 109 and 166 mg NO_3^-·L^{-1}) and decreased in the following years to between 69 and 86 mg NO_3^-·L^{-1}. The mean nitrate concentration of the water draining towards the aquifer was 120 mg NO_3^-·L^{-1} for the period 1991–1994 and 76 mg NO_3^-·L^{-1} for the period 1994–1998. It was 92 mg NO_3^-·L^{-1} for the entire period of study (1991–1998). The relative area in which the drainage water had a nitrate concentration lower than 50 mg NO_3^-·L^{-1} increased from 20–30% in the years 1991–1994 to nearly 40% in 1994–1996. This proportion reached 50% during the last year (1997–1998).

3.2.3.2. Main factors affecting the spatial and temporal variability of nitrate leaching

The impact of the previous crop, the current crop and the soil type on N leaching was examined on the basis of the annual simulation results.

The smallest nitrate concentrations were always obtained after cover crops (Fig. 6a). The average concentration over the period 1991–1998 was 45 mg N ·L–1. It varied from 18 to 87 mg ; $NO_3^- \cdot L^{-1}$ between the years. The nitrate concentrations were greater than 50 mg ; $NO_3^- \cdot L^{-1}$under all other previous crops, in particular for peas (142 mg ; $NO_3^- \cdot L^{-1}$on average), maize (120 mg ; $NO_3^- \cdot L^{-1}$) and soft winter wheat (107 mg ; $NO_3^- \cdot L^{-1}$) which were present each year, and for fallow land. The nitrate concentration was 133 mg ; $NO_3^- \cdot L^{-1}$after industrial fallow (flax, sunflower or rapeseed fallow), and 194 mg ; $NO_3^- \cdot L^{-1}$after fallow with white mustard or rye covers. The bare fallow resulted in a very large nitrate concentration of 276 mg ; $NO_3^- \cdot L^{-1}$. The impact of the current crop on nitrate leaching is difficult to analyse because it also depends on the previous crop. The effect of the current crop is linked to the rate of N uptake during winter. Figure 6b summarises the mean nitrate concentrations for each main crop. The nitrate concentration was slightly greater than 130 mg ; $NO_3^- \cdot L^{-1}$under winter wheat crops. It was 121 mg ; $NO_3^- \cdot L^{-1}$under spring crops without previous cover crops and 48 mg ; $NO_3^- \cdot L^{-1}$after cover crops. Thus, the establishment of cover crops before spring crops was very efficient since it reduced the nitrate concentration at the base of the soil profile by 73 mg ; $NO_3^- \cdot L^{-1}$. Such an effect was also observed when cover crops preceded industrial or sown-cover fallow.

Water drainage and N leaching were affected by soil type as well; they were greater in soils with a small AWC (Tab. V). It is well known that shallow soils favour water drainage and therefore N leaching, since both processes are linked. More interesting here is to observe that nitrate concentration in drainage water was also increased in these soils. The nitrate concentration in shallow soils (128 mg ; $NO_3^- \cdot L^{-1}$ on average for Rendzic Leptosols) was considerably greater than in deep soils (93 and 95 mg ; $NO_3^- \cdot L^{-1}$for Haplic Luvisols and Eutric Cambisols, respectively). Thus, soils with less agronomic potential facilitated increased N leaching and increased nitrate concentration in drainage water. This could be explained by a uniform application, including rate and spreading, of N fertiliser within each plot. Such applications led to larger values of SMN before winter in shallow soils because the yields were poorer than in deep soils, but the N fertiliser rates were identical.

3.2.4. Alternative versus conventional practices

A comparison of the impact of alternative versus conventional agricultural practices on N leaching was performed for the period 1991–1998 using continuous simulations. For the scenario corresponding to conventional practices, crop rotations and farming techniques of the period 1991–1998 were modified in order to simulate the absence of cover crops and larger N fertiliser rates, similar to the rates applied by the farmers before the action programme.

Soil type	Thickness (m)	AWC (mm)	Mean drainage (mm yr^{-1})	Mean N leaching (kg N $ha^{-1} \cdot yr^{-1}$)	Mean nitrate concentration (mg $NO_3^- \cdot L^{-1}$)
Haplic Luvisols	> 0.80	150–180	109	23	93
Eutric Cambisols	< 0.80	120–150	121	26	95
Haplic Calcisols	0.45–0.75	80–120	145	36	110
Calcaric Cambisols	0.40–0.75	60–80	168	39	103
Rendzic Leptosols	0.30–0.70	50–70	174	50	128

Table V. Mean values of drainage, N leaching and nitrate concentration in drainage water according to soil type, over the period 1991–1998.

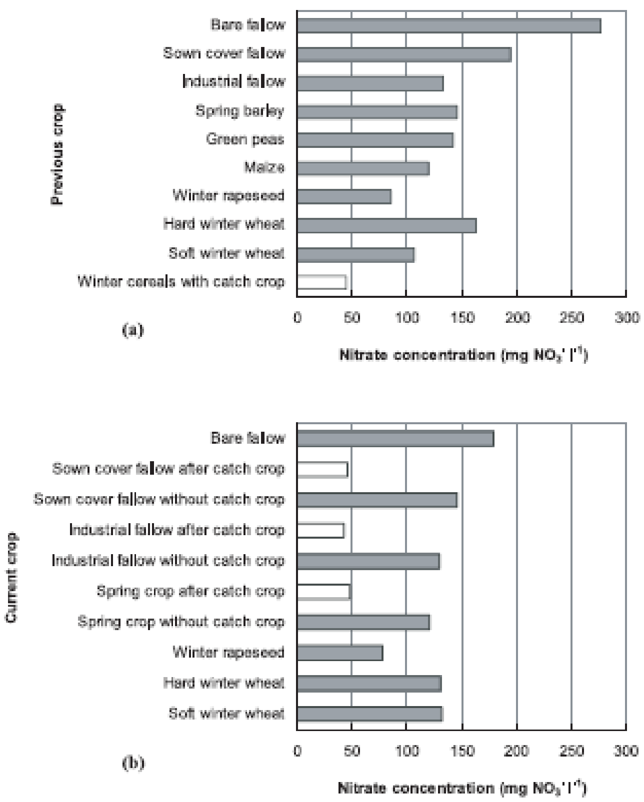

Figure 6. Mean values of nitrate concentration in drainage water according to the (a) previous crop and (b) current crop, over the period 1991–1998.

The results are expressed as mean values weighted by the SU areas (Tab. VI). They provided evidence that, over the period 1991–1998, alternative practices had reduced the mean nitrate concentration in water draining at the base of the soil of the experimental site, to between 25 and 43 mg $NO_3^- \cdot L^{-1}$, according to the year. The mean reduction of nitrate concentration estimated by the STICS model was 36 mg $NO_3^- \cdot L^{-1}$ over the entire period of study. It was slightly greater for the last four years of the action programme (1994–1998) than for the first three years (1991–1994); 38 and 34 mg $NO_3^- \cdot L^{-1}$, respectively. The mean drainage was not significantly different between alternative and conventional practices. The model predicted that cover crops had reduced drainage by 4 mm per year on average over the whole experimental site.

	Mean drainage (mm yr^{-1})		Mean N leaching (kg N·ha^{-1}·yr^{-1})		Mean nitrate concentration (mg NO_3^-·L^{-1})		
Year	(1)	(2)	(1)	(2)	(1)	(2)	(2) – (1)
91/92	50	50	19	23	164	202	38
92/93	152	154	38	51	111	147	36
93/94	192	194	35	49	82	111	29
94/95	230	234	37	59	70	112	42
95/96	111	117	19	26	75	100	25
96/97	136	138	25	38	80	123	43
97/98	141	154	24	40	74	115	41
Mean 91/94	131	132	31	41	103	137	34
Mean 94/98	155	161	26	41	75	113	38
Mean 91/98	145	149	28	41	86	122	36

Table VI. Results of continuous simulations of (1) alternative agricultural practices and (2) conventional agricultural practices, on water drainage, N leaching and nitrate concentration in drainage water, for the whole experimental site.

4. DISCUSSION AND CONCLUSION

4.1. Evaluation of the model on various scales

4.1.1. Evaluation of STICS on the plot scale

STICS was favourably evaluated on the plot scale for various combinations of cropping system, soil type and climate, and for two types of simulations: (i) the annual simulations, by initialising the model at the beginning of each crop cycle; and (ii) the continuous simulations, by using a single initialisation at the beginning of the first crop cycle. For annual simulations, we obtained at best a mean error of 1 mm (nearly 0%) and a prediction error (RMSE) of 31 mm (9%) for soil water content at harvest and, at worst, a mean error of 21 kg N·h^{-1} (27%) and a prediction error of 39 kg N·ha^{-1} (48%) for soil mineral nitrogen at harvest. SWC at harvest and water drainage were always better predicted than nitrate concentration in drainage water, which in its turn was better predicted than N leaching and SMN at harvest. The bias of the simulation was mainly related to the overestimation of nitrogen absorption by the plant at the end of the cycle and to an inadequate prediction of root density by the model under maize, particularly in soils lying on cryoturbated materials.

For the continuous simulations, the propagation of errors led to discrepancies between measured and simulated values which are more significant than those observed in the annual simulations. However, the simulated values remained in the same order of magnitude as the measured values. These results allowed us to upscale the crop model with reasonable confidence.

4.1.2. Upscaling STICS

The spatial approach of the STICS model consists of partitioning the experimental site into small simulation units (SUs) homogeneous for crops and soils, assuming that the variability within each SU is negligible [16]. This assumption is not always true; it depends on the nugget variance and the range of spatial dependence of the particular variable relative to the size of the spatial partitions [23]. Van Gardingen [42] illustrated by several examples how this approach represents a source of error for model outputs. An alternative approach would be to sample input variability in probability space instead of sampling in geographic space, or to combine these two methods [5]. Input data were collected for each homogeneous SU of the site. The soil and crop parameters required by the model were available on this scale, which is unusual. Generally, typical or recommended practices are applied uniformly within the considered area. The permanent soil properties and initial SWC and SMN profiles were estimated by pedotransfer rules and expert knowledge, respectively. This approach is effective but is likely to introduce additional errors [35, 44]. Further research should focus on analysing the different sources of error and their propagation in modelling, in order to optimise the input data from monitoring networks. Scaling up the model may require the introduction of new processes that are not taken into account on the plot scale. For example, lateral water and nitrate movements between plots may be necessary, whereas they were not considered in our spatial approach. This assumption is acceptable for the "Petite Beauce" region because of the very gentle slope and the high vertical permeability of the soils and the geological bedrock [37]. In other regions, the assumption may be false: Beaujouan [4] and Gomez [22] incorporated surface and sub-surface hydrology by embedding the STICS model within a model of a higher-level system. The performance of the STICS model's spatial approach developed in this paper was assessed across a large range of cropping systems, soil types and weather conditions, and over annual or continuous simulations. The results demonstrate the ability of the spatialised model to simulate various spatial and temporal variables with acceptable bias in the outputs.

4.2. Use of the model to simulate agricultural scenarios

The results of the case study show that the application of the STICS model's spatial approach allowed the evaluation of the impact of alternative agricultural practices on N leaching from an experimental site, over a period of seven years. The alternative practices consisted of managing N fertilisation and establishing cover crops, as recommended by the French "Code of Good Agricultural Practice". The simulations which were carried out provide evidence that N leaching towards groundwater can be markedly reduced by the implementation of the alternative practices. The mean nitrate concentration of water draining from the base of the soil profile decreased by about 30% (36 mg $NO_3^- \cdot L^{-1}$on average), over the course of the seven years. This reduction of N leaching is similar to that obtained by Lord et al. [28] with similar changes in agricultural practices. The simulations confirmed that introducing cover crops before spring crops is an effective method for reducing N leaching. The model predicted that cover crops reduced N leaching by 60% i.e. 73 mg $NO_3^- \cdot L^{-1}$. The nitrate concentration produced in plots with cover crops was, on average over the seven years of the study period, slightly lower than the EU limit for drinkable water (50 mg $NO_3^- \cdot L^{-1}$). Similar effects of cover crops have been reported in France [11, 18, 32] and in other countries [33, 41].

However, even if the situation has improved due to alternative practices, the nitrate leaching remains too high. The mean nitrate concentration simulated over the period of study was 92 mg N ·L–1. The simulation results point out the persistence, on the experimental site, of areas with a high risk of nitrate leaching; particularly those areas supporting annual fallow or green peas, and those with shallow and stony soils. Progress is still possible with the N fertiliser management of the maize crop. For the wheat crop, the market demand for higher protein content is detrimental to the environmental balance sheet. These situations suggest that further improvements to agricultural practices are required, in particular concerning the management of cultivated annual fallows, the management of the inter-cropping period after green peas, the management of N fertiliser application to maize and the management of crop residues. Variable rates of water and nitrogen applications within fields, as proposed by precision agriculture studies, could also help reduce nitrate leaching [17].

This example demonstrates the ability of a crop model spatial approach to compare the medium-term and spatial impact of different agricultural practices on nitrate leaching and to optimise these practices accordingly. Finally, this approach should, in the future, include the consequences of changing agricultural practices on crop yield, product quality, the farmer's income and water resources. Such an approach is designed to be used by the authorities responsible for establishing agricultural policy and legislation that reconciles the best interests of the farmers and the environment [34].

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REFERENCES

[1] Addiscott T.M., Whitmore A.P., Computer simulations of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring, J. Agric. Sci. (Camb.) 109 (1987) 141–157.
[2] Bastet G., Bruand A., Quétin P., Cousin I., Estimation des propriétés de rétention en eau des sols à l'aide de fonctions de pédotransfert (FPT) : une analyse bibliographique, Étude et Gestion des Sols 5 (1998) 7–28.
[3] Beaudoin N., Parnaudeau V., Mary B., Makowski D., Meynard J.M., Simulation de l'impact de différents scénarios agronomiques sur les pertes de nitrate à l'échelle d'un bassin hydrologique, in : Monestiez P., Lardon S., Seguin B. (Eds.), Organisation spatiale des activités agricoles et processus environnementaux, Sciences Update, Editions INRA, Paris, 2004.
[4] Beaujouan V., Durand P., Ruiz L., Modelling the effect of the spatial distribution of agricultural practices on nitrogen fluxes in rural catchments, Ecol. Model. 137 (2001) 93–105.
[5] Bechini L., Bocchi S., Maggiore T., Spatial interpolation of soil physical properties for irrigation planning. A simulation study in northern Italy, Eur. J. Agron. 19 (2003) 1–14.
[6] Bourennane H., King D., Le Parco R., Isambert M., Tabbagh A., Three-dimensional analysis of soils and surface materials by electrical resistivity survey, Eur. J. Environ. Eng. Geophys. 3 (1998) 5–23.
[7] Brisson N., Gary C., Justes E., Roche R., Mary B., Ripoche D., Zimmer D., Sierra J., Bertuzzi P., Burger P., Bussière F., Cabidoche Y.M., Cellier P., Debaeke P., Gaudillère J.P., Hénault C., Maraux F., Seguin B., Sinoquet H., An overview of the crop model STICS, Eur. J. Agron. 18 (2003) 309–332.
[8] Brisson N., Mary B., Ripoche D., Jeuffroy M.H., Ruget F., Nicoullaud B., Gate P., Devienne-Barret F., Antonioletti R., Durr C., Richard G., Beaudoin N., Recous S., Tayot X., Plenet D., Cellier P., Machet J.M., Meynard J.M., Delécolle R., STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn, Agronomie 18 (1998) 311–346.
[9] Brisson N., Ruget F., Gate P., Lorgeou J., Nicoullaud B., Tayot X., Plenet D., Jeuffroy M.H., Bouthier A., Ripoche D., Mary B., Justes E., STICS : a generic model for simulating crops and their water and nitrogen balances. II. Model validation for wheat and maize, Agronomie 22 (2002) 69–92.
[10] Carlotti B., Recueil des bases de préconisations de la fertilisation azotée des cultures, Ministère de l'Agriculture, Ministère de l'Environnement, Mission Eau Nitrates, CORPEN, Paris, 1992.
[11] Chapot J.Y., Schwab G., Huck C., Le dispositif lysimétrique de Colmar. Étude de l'incidence de l'introduction de cultures pièges à nitrates, pendant l'interculture, sur les flux d'eau et d'azote, in : Muller J.C. (Ed.), Trente ans de lysimétrie en France, 1960–1990, Editions INRA, Paris, 1996, pp. 151–168.
[12] Chéry P., Variabilité de l'épaisseur de la couverture de sol. Conséquences pour le bilan hydrique hivernal d'un secteur de Petite Beauce, Ph.D. thesis, Université de Nancy I, France, 1995, 253 p.
[13] Chéry P., Variabilité verticale de la composition granulométrique des limons de Petite Beauce (France), Étude et Gestion des Sols 6 (1999) 185–196.
[14] CORPEN, Propositions du CORPEN pour le Code de Bonne Pratique Agricole, Ministère de l'Agriculture, Ministère de l'Environnement, Mission Eau Nitrates, CORPEN, Paris, 1993.
[15] Coutadeur C., Cousin I., Influence de la phase caillouteuse sur la réserve en eau des sols - Cas des sols de Petite Beauce du Loiret, Étude et Gestion des Sols 7 (2000) 191–205.

[16] de Jager J.M., Potgieter A.B., van den Berg W.J., Framework for Forecasting the Extent and Severity of Drought in Maize in the Free State Province of South Africa, Agric. Syst. 57 (1998) 351–365.
[17] Dinnes D.L., Karlen D.L., Jaynes D.B., Kaspar T.C., Hatfield J.L., Colvin T.S., Cambardella C.A., Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils, Agron. J. 94 (2002) 153–171.
[18] Dorsainvil F., Évaluation, par modélisation, de l'impact environnemental des modes de conduite des cultures intermédiaires sur les bilans d'eau et d'azote dans les systèmes de culture, Ph.D. thesis, INA-PG, France, 2002, 183 p.
[19] Duval O., Isambert M., Notice explicative de la carte pédologique de Villamblain (Beauce) au 1/10 000e, SESCPF-INRA, Orléans, France, 1992, 38 p.
[20] ESRI, Arc/Info 7.2.1: User's Guide, Environmental Systems Research Institute, Redlands, CA, 1999.
[21] FAO, Soil Map of the World. Revised Legend, 60, Rome, 1988. [22] Gomez E., Ledoux E., Démarche de modélisation de la dynamique de l'azote dans les sols et de son transfert vers les aquifères et les eaux de surface, C.R. Acad. Agric. France 87 (2001) 111–120.
[23] Hansen J.W., Jones J.W., Scaling-up crop models for climate variability applications, Agric. Syst. 65 (2000) 43–72.
[24] Hansen S., Thorsen M., Pebesma E.J., Kleeschulte S., Svendsen H., Uncertainty in simulated nitrate leaching due to uncertainty in input data. A case study, Soil Use Manage. 15 (1999) 167–175.
[25] Hartkamp A.D., White J.W., Hoogenboom G., Interfacing Geographic Information Systems with Agronomic Modeling : A review, Agron. J. 91 (1999) 761–772.
[26] Lacroix A., Beaudoin N., Makowski D., Agricultural water nonpoint pollution control under uncertainty and climate variability, Ecol. Econ. (2004) (in press).
[27] Lord E.I., Anthony S.G., MAGPIE: A modelling framework for evaluationg nitrate losses at national and catchment scales, 16 (2000) 167–174.
[28] Lord E.I., Johnson P.A., Archer J.R., Nitrate Sensitive Areas : a study of large scale control of nitrate loss in England, Soil Use Manage. 15 (1999) 201–207.
[29] Macaire J.M., Sur le limon de Beauce au Nord-Ouest d'Orléans (Loiret), C.R. Acad. Sci. Paris 274 (1972) 1892–1895.
[30] Macaire J.M., Contribution à l'étude géologique et paléopédologique du Quaternaire dans le Sud-Ouest du Bassin de Paris (Touraine et ses abords), State thesis, Université de Tours, France, 1981.
[31] Machet J.M., Dubrulle P., Louis P., AZOBIL: a computer program for fertiliser N recommendations based on a predictive balanceshe et method, in : Proceedings of 1st Congress of the European Society of Agronomy, Paris, 1990.
[32] Machet J.M., Laurent F., Chapot J.Y., Dore T., Dulout A., Maîtrise de l'azote dans les intercultures et les jachères, in : Lemaire G., Nicolardot B. (Eds.), Maîtrise de l'azote dans les agrosystèmes, INRA Editions, 1997, pp. 271–288.
[33] Meisinger J.J., Hargrove W.L., Mikkelsen R.L., Williams J.R., Benson V.W., Effects of cover crops on groundwater quality, in : Hargrove W.L. (Ed.), Cover crops for clean water, Conservation Society, Jackson, Tennessee (USA), 1991, pp. 57–68.
[34] Meynard J.M., Cerf M., Guichard L., Jeuffroy M.H., Makowski D., Which decision support tools for the environmental management of nitrogen? Agronomie 22 (2002) 817–829.
[35] Morvan X., Bruand A., Cousin I., Roques J., Baran N., Mouvet C., Prédiction des propriétés de rétention en eau des sols d'un bassin versant à l'aide de fonctions de pédotransfert : influence de la densité apparente et de la teneur en éléments grossiers, Étude et Gestion des Sols (2004) (in press).
[36] Nicoullaud B., Couturier A., Beaudoin N., Mary B., Coutadeur C., King D., Modélisation spatiale à l'échelle parcellaire des effets de la variabilité des sols et des pratiques culturales sur la pollution nitrique agricole, in: Monestiez P., Lardon S., Seguin B. (Eds.), Organisation spatiale des activités agricoles et processus environnementaux, Sciences Update, Editions INRA, Paris, 2004.

[37] Ould Mohamed S., Bruand A., Bruckler L., Bertuzzi P., Guillet B., Raison L., Estimating long-term drainage at a regional scale using a deterministic model, Soil Sci. Soc. Am. J. 61 (1997) 1473–1482.
[38] Rémy J.C., Hébert J., Le devenir des engrais azotés dans le sol, C.R. Acad. Agric. France 63 (1977) 700–710.
[39] Ruget F., Brisson N., Delécolle R., Faivre R., Sensitivity analysis of a crop simulation model, STICS, in order to choose the main parameters to be estimated, Agronomie 22 (2002) 133–158.
[40] Schnebelen N., Analyse et modélisation de l'impact de la maîtrise des pratiques agricoles sur la pollution diffuse par les nitrates. Application à l'aquifère des Calcaires de Beauce (site de Villamblain), Ph.D. thesis, Université d'Orléans, France, 2000, 363 p.
[41] Shepherd M.A., The effectiveness of cover crops during eight years of a UK sandland rotation, Soil Use & Manage. 15 (1999) 41–48.
[42] van Gardingen P.R., Foody G.M., Curran P.J., Scaling-up from cell to lanscape, Cambridge University Press, 1997.
[43] Verbèque B., Revalier C., Mise en oeuvre d'une gestion raisonnée de l'azote en Petite Beauce, Secteur de Villamblain, Service Environnement-Agronomie et Laboratoire de la Chambre d'Agriculture du Loiret, Orléans, France, 1999, 63 p.
[44] Voltz M., Lagacherie P., Louchart X., Predicting soil properties over a region using sample information from a mapped reference area, Eur. J. Soil Sci. 48 (1997) 19–30.
[45] Zanolin A., Irrigation de précision en Petite Beauce : mesures au champ et modélisation stochastique spatialisée du fonctionnement hydrique et dynamique d'une parcelle de maïs, Ph.D. thesis, Université de Paris 6, France, 2003, 187 p.